VOLUME 79 SEPARATE No. 218

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

JULY, 1953

WIND VELOCITIES DURING HURRICANES

by Robert C. Gentry

Presented at
Miami Beach Convention
June 16-19, 1953

STRUCTURAL DIVISION

{Discussion open until November 1, 1953}

Copyright 1953 by the AMERICAN SOCIETY OF CIVIL ENGINEERS
Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

THIS PAPER

--represents an effort of the Society to deliver technical data direct from the author to the reader with the greatest possible speed. To this end, it has had none of the usual editing required in more formal publication procedures.

Readers are invited to submit discussion applying to current papers. For this paper the final closing dead line appears on the front cover.

Those who are planning papers or discussions for "Proceedings" will expedite Division and Committee action measurably by first studying the printed directions for the preparation of ASCE technical papers. For free copies of these directions—describing style, content, and format—address the Manager, Technical Publications, ASCE.

Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

The Society is not responsible for any statement made or opinion expressed in its publications.

This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

WIND VELOCITIES DURING HURRICANES

Robert C. Centry

ABSTRACT

The following topics are discussed: structure of hurricanes, duration of winds, forces acting on air particles, distribution of wind velocity in hurricanes, wind data, gust factors, variation of velocity with height, and probability of hurricane occurrence. Examples of highest velocities measured and estimates of highest hurricane winds ever observed in this country are given. Averages are furnished of the following ratios: peak gust velocity to velocity of fastest mile, and peak gust velocity to highest 5-minute average velocity. Because of lack of data for computing variation of velocity with height, it is recommended that the one-seventh power law be used to approximate the variation of the wind velocity with height up to 1000 feet above which a constant velocity should be used.

WIND VELOCITIES DURING HURRICANES

Robert C. Gentry

INTRODUCTION

In the long fight of man against hurricanes, one of the courses of action followed to reduce accident and death rates and property losses, has been the building of "hurricane proof" structures. This paper was prepared to give the designing engineer more complete information as to the strength of the winds and gusts in hurricanes. In the first part of the paper, there is a brief discussion of the type of storm with which we are dealing. In the last part of the paper, is a group of data giving velocity of winds observed in some of our more violent hurricanes. There is also included some data concerning gusts that are experienced in hurricanes. Insofar as it was practical, original Weather Bureau records were consulted for the data.

DEFINITIONS

Technical terms used in the paper are defined as follows:

Wind Velocity.--Speed (miles per hour) and direction of air movements with respect to the ground.

Maximum Velocity.--Highest average velocity, during five consecutive minutes of any storm (V_5).

Extreme Velocity.--Average velocity during the time the fastest mile of wind was passing a point during the storm (V_m).

Gust.--Localized high wind velocity lasting a short time.

Gust Velocity.--Instantaneous velocity as measured by either the 3 or 4 cup anemometer unless indicated otherwise (V_i).

Gust Factor.--Ratio of highest gust velocity to maximum velocity (at a station) for same storm, (not necessarily measured during the same 5-minute period).

Gust Ratio.--Ratio of highest gust velocity to extreme velocity at a station for the same storm (not necessarily measured during the same period).

Eddy.--A group of air parcels with components of motion transverse to the general stream.

Surface Wind.--Wind vector in the layers near the ground--usually at the height of the wind instruments which in most cases are erected at heights of 30 to 150 feet above the ground.

Gradient Wind.--Wind vector in steady flow above the layer influenced by ground friction.

Isobar.--Locus of points of equal atmospheric pressure, and when shown as line on weather map will be for some particular level, i.e., sea level, 10,000 feet, etc.

Pressure Gradient.--Rate of change of atmospheric pressure per unit distance. Pressure gradient is shown graphically on weather map by spacing of isobars; i.e., isobars close together indicate strong gradient, and isobars with rela-

tively large spaces between them indicate weak gradient.

Hurricane Force Winds.--Greater than 75 mph.

Hurricane.--A storm of tropical origin with winds of hurricane force revolving (counter-clockwise in northern hemisphere) around a central area that is relatively calm. The atmospheric pressure inside the center is less than outside the circulation. In other parts of the world, the same type storm is known by such names as typhoons, tropical cyclones, willy-willies, and baguios.

Eye of Hurricane.--Central area of the storm in which the winds are relatively light.

STRUCTURE OF HURRICANES

The surface winds of the hurricane blow around, and at the same time, spiral in toward the center at least until they approach the inner wall of the storm. In this area, one usually finds the strongest winds and worst weather. The converging air currents ascend in this area which cause huge build-ups of clouds, torrential rain, and many strong eddies. Inside of this inner wall, at the center of the storm, is the eye. Passing into the eye, one would experience a sudden decrease in the wind velocity, a cessation of most or all of the rain, and many times one could see blue skies over-head. The hurricane is a warm-core storm, i.e., the air in the eye is warmer than that in either the surrounding circulation, or the air surrounding the whole hurricane. This warm air

is believed to have been brought down from above by subsiding air currents in the eye, and the air warms while descending due to being compressed. The eye will extend to the top of the storm, however, the walls and the axis of the eye are not necessarily vertical. Although the air in the lower layers of the storm is moving along a spiral, the radius of the spiral is so great, an observer at any one fixed point would not be able to detect the curvature in the air trajectory. Hurricanes vary in height just as they vary with intensity. Being a warm core storm, the difference in the pressure gradient from the center to the outer edge of the storm must decrease with height. Although there are other factors which may partially compensate, this will cause the storm to decrease with intensity at some height above the surface. This level will vary from storm to storm, but will usually be in the vicinity of 4000 to 25,000 feet.

Diameters of hurricanes range from a few miles to hundreds of miles. The size of the eye also varies. Storms have been reported in which the eye was as small as 3 miles in diameter, or as large as 50 miles (sometimes even larger in decaying dispersing storms). In the October 1950 hurricane, the area of really destructive winds was only 14 miles wide, and the eye was only 5 miles wide at the time the storm passed over Miami, according to Norton (11).

Maximum wind velocity observed by a land station in this storm was 97 mph and extreme velocity was 122 mph. By contrast, the hurricane of September 10-19, 1947, had hurricane force winds over an area of 240 miles in diameter at the time it approached the Florida coast. Typhoons are frequently observed in the Pacific in which the area of winds of over 75 mph cover an area of over 500 miles in diameter.

The maximum velocity of a storm is not necessarily correlated with either the size of the hurricane nor with the central pressure. It is, however, highly correlated with the maximum intensity of the pressure gradients within the storm.

DURATION OF WINDS WITHIN A HURRICANE

Once a hurricane has formed, it will nearly always persist until one of three things happen: (1) it moves over rough terrain and is dissipated, (2) cold air gets into the wind system (this seldom happens until the storm has moved into the more northern latitudes), or (3) dry air gets into the circulation. Therefore, in the tropics, once a hurricane is formed, the chances are good that the winds will remain of destructive intensity for many days. As to the duration of winds of hurricane force at any one point, there are two factors to be considered: (1) the area of destructive winds in the hurricane, and (2) the speed with which the hurricane is moving. In the Atlantic, the diameter of the destructive

wind area will usually be about 15 to 300 miles. The average movement of the hurricane will usually be about 15 mph. Thus a hurricane should pass a point in 1 to 20 hours. However, hurricanes seldom follow the averages. Some hurricanes move much faster than 15 mph and others stagnate in an area and move very little for several days. Fortunately in the past, most of these latter cases have occurred over water with no land area close by, however, there is no reason why in the future, a large hurricane could not stagnate close to a coast and give hurricane force winds to some city for 72 hours or longer.

FORCES ACTING ON WINDS IN HURRICANES

Exclusive of the frictional drags, there are three forces acting on air particles in a hurricane. The hurricane is a low pressure system, i.e., the atmospheric pressure in the center of the storm is lower than it is on the outer edge of the storm. Thus there is a pressure force acting to force the air in toward the center of the storm. This force gives an acceleration proportional to the ratio of the pressure gradient and the density of the air ($\frac{1}{\rho}\frac{dp}{dn}$ where ρ is density of the air and $\frac{dp}{dn}$ is the rate of change of pressure measured along the normal vector, n). The path of the air has two horizontal deflective forces due to its velocity: one caused by the air moving over a rotating sphere, the earth; and the other caused by the air moving

in a curved path. Following Humphrey's derivation(5), acceleration from the first force is $2\omega v \sin\phi$ where ω is the angular velocity of the earth, v is the velocity of the air, and ϕ is the latitude. Acceleration from the second horizontal deflective force is $\frac{v^2}{r}$ where r is the radius of curvature of the air path. When the winds become approximately steady, the deflective forces balance the pressure gradient and

$$\frac{1}{\rho}\frac{dP}{dn} = 2\omega v \sin\phi + \frac{v^2}{r} \qquad (1)$$

Solving this equation for v,

$$v = \sqrt{\frac{r}{\rho}\frac{dP}{dn} + (r\omega\sin\phi)^2} - r\omega\sin\phi \qquad (2)$$

which is the equation of the gradient wind. This is what the wind should be in a hurricane above the layer of frictional influence if there are no accelerations. In low latitudes, $\sin\phi$ is much less than 1 and with hurricane force winds, v is much less than v^2. Therefore, to a close approximation

$$\frac{1}{\rho}\frac{dP}{dn} = \frac{v^2}{r} \qquad (3)$$

$$v = \sqrt{\frac{r}{\rho}\frac{dP}{dn}} \qquad (4)$$

Thus there is a good physical reason for a high correlation between the velocities and the pressure gradients of a storm.

We have data giving variation of $\frac{1}{\rho}\frac{dp}{dn}$ with height in several hurricanes. James(9) analyzed data from Tampa taken during the hurricane October 19, 1944, and found that this ratio

remained relatively constant up to 10,000 feet and then decreased in value with greater altitudes. For the typhoon which passed over Tokyo on August 31, 1949, he found the ratio remained relatively constant with height up to about 27,000 feet. At higher levels, it decreased in value. For averages computed by Schacht(12) for several hurricanes, James also found that the ratio remained relatively constant in the lower levels of the atmosphere. Therefore, to the extent that balanced flow prevails in a hurricane, the winds of a hurricane should remain almost constant with height in the lower levels of the atmosphere (at least below 3000 feet) once one gets above the layer of frictional influence (about 1000 feet). What little data we have, indicate that balanced flow is only a very rough description of what takes place in a hurricane, and once data are available, we may find that the velocity varies with height. However, until more data are available, an assumption of constant velocity with height in the layer from 1000 feet to 3000 feet (and in mature, intense storms, to considerably higher levels) seems to be as good as any we can make.

DISTRIBUTION OF WIND VELOCITY IN HURRICANES

Although every hurricane is a law unto itself, on the average, winds increase toward the center of the hurricane until the radius of maximum velocity which is relatively near the center. As the first approximation to a horizontal

velocity profile of a hurricane, Cressman(1) assumed that solid rotation existed from the edge of the hurricane eye out to a distance r_1, where a maximum value of $r\Omega$ is found. Here r is the radius of curvature of an air particle and Ω is its angular velocity. He further assumed that from r_1 to R a vr^{n-1} vortex exists where R is the radius of the outer boundary of the vortical circulation of the hurricane. According to Cressman, "Various studies by McDonald(10) U. S. Weather Bureau forecasters(15), and James(8) have suggested that n varies from values of slightly greater than 2 for small immature systems to values near 3/2 for large mature typhoons.

Data from individual storms show there are many variations from this idealized profile. On the average, the right front quadrant (when facing the direction toward which the storm is moving) will have stronger winds than the other quadrants and one of the left quadrants will have the weakest winds. However, there are exceptions. Some storms have their strongest winds to the left of the center, and others have the strongest behind the center. Although in general, the strongest winds are near the boundary of the eye, sometimes they are far removed. This is particularly true in the case of non-symetrical developing storms or of mature storms which have becomedistorted due to passing over land.

DATA

Hurricane data have been collected and preserved by the Weather Bureau since it was organized in the latter part of the 19th Century. The Monthly Weather Review each year carries a summary of the season's hurricane activity in which accounts are given of each storm, maximum and extreme winds observed, damage caused, etc. Tannehill has summarized most of these data and collected many more extending back to the year 1494 in his book Hurricanes(14). From all of these data, one would think it should be easy to get an accurate idea of the highest wind velocities that can be expected in hurricanes. However, the problem is complicated by the fact that wind instruments may not be exposed at the proper location to measure the highest winds. As pointed out in the previous discussion concerning the winds of a hurricane, the highest velocities may cover only a relatively small area. If this most intense portion of the storm does not pass over a weather station at or near the coastline, no measurement is secured of the highest velocity because the storm starts decreasing in intensity soon after passing over land. The Florida Keys hurricane of September 1935 set a new record for the lowest atmospheric pressure ever measured at sea level over land, and from the destruction it caused, was undoubtedly the most severe hurricane to affect the United States since records have been kept. However, it did not go near an anemometer during the time

it was at its peak intensity, and we have only estimates of its maximum and extreme velocities. Securing measurements of the highest velocities ever experienced in hurricanes is further complicated by the fact that anemometers often fail when the wind velocity gets well above 100 mph. Tannehill(14) writes, "One very serious problem in designing wind-measuring devices arises from the requirement that the instrument be sufficiently sensitive to respond to variations at moderate velocities and yet be sturdy enough to withstand the winds of the hurricane. In many violent hurricanes, the wind instruments have been damaged or blown away before the highest storm winds were experienced. In some instances, the steel towers which supported the anemometers have been wrecked. In other cases, the buildings on which the instruments were exposed have been destroyed or unroofed". As will be shown later, the highest maximum velocity measurement secured in the United States was made by an anemometer just before it became inoperative and probably before the highest velocities had been experienced.

Any attempt to get an estimate of the gust factor, the gust ratio, or the variation of the various velocity measurements with height, is also complicated by lack of proper instruments in the right place at the right time. Indeed it would be very expensive to set up a station to obtain data concerning variation of velocity with height under proper controls as was pointed out by Sherlock(13). Even if money were no object, one might need quite a bit of luck to

secure the data in any reasonable length of time. For instance, the probability of hurricane occurrence along the southeast Florida Coast is as high as anywhere else in the United States. However, from 1900 to 1926, no hurricane force winds were observed in Miami.

Most of the Weather Bureau and other co-operating Weather Services make wind measurements with either a 3 or 4 cup anemometer. Some of the anemometers are connected with either a double or triple register which records the passage of each mile of wind on a revolving drum which is driven by a clock. From these records, it is easy to obtain the extreme velocity and also the maximum velocity, but it is not feasible to make any estimate of the gust velocity. In some of these offices and at many others, a buzzer is connected to the anemometer which buzzes at every 60th of a mile. By counting the number of buzzes per minute, one gets the velocity in miles per hour. By this method, a careful observer can measure the maximum and extreme velocities, but estimates of the gust velocities are unsatisfactory when the winds are above 100 mph. At other stations, the anemometer is connected to a direct reading dial which gives the instantaneous wind velocity (within the limits that it is measured by the anemometer). From this arrangement, a careful observer can get a good estimate of the gust velocity and an acceptable estimate

of the extreme velocity (fastest mile). In recent years, offices without the double or triple register usually have not made a measurement of the maximum velocity (i.e. the highest average velocity for 5 consecutive minutes). Therefore, our data are in two groups: (1) from stations where extreme and maximum velocity measurements were made, and (2) from stations where gust and extreme velocity measurement were made.

EXAMPLES OF HIGH VELOCITIES

All previous records of hurricane winds were exceeded at San Juan, Puerto Rico, September 13, 1928 when at 11:44 A.M. the anemometer at the office of the United States Weather Bureau lost one of its cups--just after recording a maximum velocity of 135 mph and an extreme velocity of 144 mph. At this time, the storm center was about 30 miles away. In the words of Oliver L. Fassig, Meteorologist in Charge, "the storm increased in intensity for 3 hours after the record... was made. Most of the damage to the property on the Weather Bureau Reservation occurred between 2:30 and 3:30 P.M. ..... With only two cups the anemometer still recorded about 75 mph. The second cup disappeared at 12:47 P.M. The arms and the shaft of the anemometer with one cup still attached were blown away at 1:33 P.M.; these parts were later found..... a third of a mile to the southwest...." (2)

In the great New England hurricane of September 1938, a

maximum velocity of 121 mph was observed at the Blue Hill Observatory, Milton, Massachusetts. A velocity of 186 mph was observed for a shorter period. This probably exceeds any other velocity measured for hurricanes, but its representativeness is open to doubt. The observatory is on top of a hill and some of the velocity may have been due to the orographic effect, i.e., winds in the hurricane flowing over level ground may not have been that strong. An extreme velocity of 155 mph was measured at Hillsboro Lighthouse, Florida, September 17, 1947. The maximum velocity for the same storm at that station was 121 mph. The anemometer at Hillsboro is 146 feet above the ground.

During the August hurricane of 1949, a maximum velocity of 132 mph was measured at Jupiter Lighthouse before the instrument failed, and this is believed to be the highest measured during a hurricane in the United States. The extreme velocity was 153 mph. The observer at Jupiter where the anemometer is 106 feet above the ground, reported that winds became stronger after the instrument failed; but he felt unable to make a reliable estimate of the extreme velocity.

The Florida Keys Hurricane which passed over Lower Matecumbe Key September 2, 1935, undoubtedly had stronger winds than any that have been measured. Its lowest atmospheric pressure was measured as equivalent to that of 26.35 inches

of mercury which is the world's record for sea level readings at land stations. (Lower readings have been made at sea.) When the August 1949 hurricane crossed the coastline, its minimum pressure reading was down to only 28.17 inches. Furthermore, the diameter of the Keys storm was much less than the Jupiter storm, so the difference in pressure gradients would be even greater than the difference in the minimum pressures. Since the strength of the winds is of necessity highly correlated with the pressure gradients, it is obvious that the winds should have been much stronger in the Keys storm than in the Jupiter storm. It is quite possible that the winds reached or exceeded a velocity of 200 mph. Computations of the surface wind velocity both from the pressure gradient using the equation of motion, and from the structural damage using the stress equations indicated that the velocity exceeded 200 mph.

In addition to the high winds regularly observed in hurricanes, several tornadoes have occurred in Florida along the northern periphery of hurricanes. No measurement has ever been made of the winds in these tornadoes since they usually affect a relatively small area and none has passed over a weather station. However these winds are believed to exceed 200 mph considerably.

GUST FACTOR AND GUST RATIO

Data from nine hurricanes from 1944 through 1950 were analyzed to get an estimate of the gust factor. Only data from stations having hurricane force winds were used. The stations were divided into two groups. Four stations with instruments at levels of 146 to 226 feet were put in one group, and all the other stations with instruments at lower levels were put in the other group. Range of elevation of instruments in the second group was from about 30 feet to about 110 feet. In group one, data were available to calculate only the ratio of the extreme to the maximum velocity. Mean, maximum, and minimum ratios for the two groups and number of cases used to compute the means are given in Table I. There was no difference in the ratio of $\frac{V_m}{V_5}$ for the two groups of stations; so we are unable to give any variation in the gust ratio or gust factor with height from data available.

Table I

Height Above Ground	V_i/V_m Mean	Max.	Min.	V_i/V_5 Mean	Max.	Min.	V_m/V_5 Mean	Max.	Min.
30-110'	1.2 (12)	1.6	1.1	1.3 (13)	1.7	1.1	1.2 (33)	1.8	1.0
146-226'							1.2 (12)	1.3	1.0

(Figures in parentheses are the number of cases used to compute the respective means.)

For the stations with lower elevations, values are given for the ratio of the gust velocity to the maximum velocity, i.e., the gust factor. However, as explained earlier, for stations equipped only with the double or triple register and a buzzer, it is very difficult to get an accurate estimate of the gust velocity when winds are strong. Since

$$\frac{V_i}{V_m} \times \frac{V_m}{V_5} = \frac{V_i}{V_5}$$

which is the ratio used for the Gust Factor, the writer believes a more accurate estimate of the latter is obtained by calculating the product of the first two ratios. In this case, the gust factor would be 1.4 rather than the 1.3 indicated by the actual estimates made by observers. This value compares closely with values obtained in study of non-hurricane winds carried out with special instrumentation on specially constructed towers. Sherlock(13) found that at levels from 25 feet to 150 feet, the gust factor in a winter storm averaged from 1.3 to 1.4 In 1945-46, The Daniel Guggenheim Airship Institute Division of the University of Akron, Akron, Ohio, under contract to the U. S. Weather Bureau, conducted an investigation to determine (1) the variation of wind velocity with height, (2) the ratio of extreme gust velocities to average wind velocities, and (3) the variation of the gust ratio with height. The results are presented in an unpublished report by Huss(7),

They found that the mean gust factor at levels 40 feet, 100 feet and 160 feet were 1.6, 1.4, and 1.4 respectively, with individual values at those levels ranging from 1.9 to 1.2. The gust ratios for the same three levels were 1.5, 1.3, and 1.3, which are all higher than the value, 1.2, given in Table I for the hurricane force winds.

The data collected for the hurricanes from 1944 through 1950 were also examined to see if there were any correlation between the gust factor and the speed of the wind. No significant correlation was found in the data available.

VARIATION OF VELOCITY WITH HEIGHT ABOVE GROUND

From the hurricane data available, it is impossible to make any good deductions concerning the variation of the wind with height in the more violent portions of the storm. To do this it would be necessary to have two or more wind measuring instruments installed at the same station at different heights, and we do not have such a station. The winds within a hurricane vary so much in velocity within even short distances that it is not permissible to compare readings at two neighboring stations and attribute the differences in the velocities to the difference in heights of the anemometers.

During the Daniel Guggenheim Airship Institute Division of the University of Akron and United States Weather Bureau investigation mentioned earlier, this problem of variation

with height was attacked. Huss(7) wrote, "It was found that the variation of velocity with height could be represented by the equation

$$V/V_o = (h/h_o)^{1/n},$$

where V_o is the velocity at height h_o = 100 feet, and V is the corresponding velocity at any height h, not to exceed 350 feet (in region of observation only, although limited extrapolation beyond 350 feet may be fairly reliable). The value of n was found to vary with height, and with the type of velocities considered, (V_i, V_m, V_5). Mean values of n at each level for the maximum and extreme velocities are given in the following table.

TABLE II

	Height Above Ground				
	40 ft.	160 ft.	220 ft.	280 ft.	350 ft.
n for maximum velocities	3.4	5.2	6.3	5.8	6.4
n for extreme velocities	3.4	5.8	7.5	4.1	6.8

"These values of n agree favorably with those obtained in earlier investigations. Hellman(6) obtained an identical expression, and found values of n=8 for h greater than 16 meters, and n=5 for h greater than 32 meters."

Working with his data, Sherlock(13) independently came to the conclusion that the same expression with n=7 gave good results when h_o=30 feet. Since all these investigations arrived at similar conclusions, the writer believes that a

satisfactory assumption would be to use the values furnished by Sherlock for levels up to 1000 feet; and then assume a constant velocity on up to at least 3000 feet in accordance with the discussion given earlier.

PROBABILITY OF OCCURRENCE OF HURRICANE FORCE WINDS

All of the states along the Gulf and Atlantic coasts are occasionally visited by hurricanes. However, the frequency is much higher in some areas than others. In Table III is a tabulation of the number of tropical storms that gave hurricane force winds in different areas from 1900 to 1951.

The summary reveals that the number of hurricanes was slightly greater in extreme south Florida (Greater Miami and Cape Sable southward through the Keys) than for any other equal length of coastline. Texas ranked second in frequency with northwestern Florida and Alabama (Apalachee Bay area west to Mississippi) third. The areas listed in the Table are in order of descending frequency per unit length of coastline. The total number of hurricanes shown for each area is significant only when compared with those for other sections of similar size. For instance, Texas shows 23, and extreme south Florida 18, but Texas represents a longer length of coastline. The high frequency for North Carolina is largely due to the exposed position of Cape Hatteras, which juts out into the Atlantic near

the path of so many storms. Actually, the frequency of hurricanes in sections of North Carolina other than the sparsely settled Capes is rather low. Table III was prepared by Gentry, Moore, and Marshall(3) and they emphasized that the statistics given are based on only 52 years of data. Frequencies in the future may be quite different.

TABLE III

HURRICANES-- 1900 through 1951 (Areas listed according to relative number of hurricanes per length of coastline)

Area	No. of Tropical Storms Giving Hurricane Force Winds in Area
Extreme South Florida (Miami--Cape Sable southward through Florida Keys)	18
Texas	23
Alabama and Northwest Florida (Apalachee Bay area to Mississippi)	18
Florida West Coast (South of Apalachee Bay and north of Cape Sable)	13
Louisiana and Mississippi	16
North Carolina	10
Eastern Florida (North of Greater Miami)	16
Georgia	3
South Carolina	3
Virginia	5
Maryland, Delaware, and New Jersey	4
New York and New England	5

Grady Norton(4) studied all available records and prepared some data indicating the chance of Florida cities having

hurricane winds. He writes, "Table 4 has been prepared to indicate roughly the chances in any given year for a hurricane in the areas in, and adjacent to, several of the principal coastal cities of Florida. This table is based on a record of only 63 to 75 years in length, and it should be kept in mind that this is too short to indicate the expectancy with any high degree of adcuracy. The records of the past 20 years have materially changed these figures, and the records in the future years may further alter them."

"Table 4

CHANCES OF HURRICANE FORCE WINDS IN ANY GIVEN YEAR

Cities	Chances	Cities	Chances
Jacksonville	1 in 50	Key West	1 in 7
Daytona Beach	1 in 30	Fort Myers	1 in 12
Melbourne-Vero Beach	1 in 20	Tampa-St. Petersburg	1 in 20
Palm Beach	1 in 10	Apalachicola-St. Marks	1 in 15
Miami	1 in 7	Pensacola	1 in 10

(Figures are weighted averages based on all available records)"

SUMMARY

A few hurricanes can be expected to give extreme velocities of about 150 mph at a height of 100 feet above the ground. In the last 75 years, there has been one hurricane with an estimated extreme velocity of over 200 mph. Gusts in hurricanes average about 20 per cent higher than the extreme velocities, and there is little or no correlation between the extreme velocity and the gust ratio. In the absence of proper data for establishing a definite relationship, the one-seventh power law should be used to approximate the

variation of the wind velocity with height up to 1000 feet, above which a constant velocity should be used. The limited data available indicated little or no variation of gust factors with height.

References

(1) Cressman, George P., "The Development and Motion of Typhoon 'Doris', 1950, Bulletin American Meteorological Society, vol. 32, No. 9, Nov., 1951, p. 332.

(2) Fassig, Oliver L., "San Felipe--The Hurricane of September 13, 1928, at San Juan, P. R.," Monthly Weather Review, vol. 56, No. 9, Sept. 1928, p. 351.

(3) Gentry, R. C., Moore, P. L., and Marshall, A. M., Hoist Hurricane Warnings, Weather Vane Publications, Miami Springs, Florida, 1950.

(4) Gray, Richard W., revised by Norton, Grady, "Florida Hurricanes", Government Printing Office, 1949, p. 1.

(5) Humphreys, W. J., Physics of the Air, McGraw-Hill Book Company, Inc., New York, 1940, pp. 119-120.

(6) Hellman, G., "Uber die Bewegung der luft in den untersten Schickten der Atmosphere", Met. Zeit. Band 34, p. 273, 1917 and Preuss. Akad. Wiss. Berlin, Beitrage 22, p. 404, 1919.

(7) Huss, P. O., "Relation between Gusts and Average Winds for Housing Load Determination", Unpublished report of Daniel Guggenheim Airship Institute, June 1946.

(8) James, R. W., 1951, "On the Evolution of Tropical Cyclones", Journal of Meteorology, Vol 8, No. 1, pp 17-24

(9) James, R. W., "A Note on the Vertical Structure of a Typhoon", Monthly Weather Review, vol 79, No. 11, Nov. 1951, pp 205-07

(10) McDonald, W. F., "On a Hypotheses Concerning the Normal Development and Disintegration of Tropical Hurricanes", Monthly Weather Review, vol 70, No. 1, Jan. 1942, pp. 1-6

(11) Norton, Grady, "Hurricanes of the 1950 Season", Monthly Weather Review, Vol. 79 No. 1, Jan. 1951, p. 14.

(12) Schacht, E. J., "A Mean Hurricane Sounding for the Caribbean Area", Bulletin of the American Meteorological Society, vol. 27, No. 6, June 1946, pp 324-327.

(13) Sherlock, R. H., "Variation of Wind Velocity and Gusts with Height", Proceedings American Society of Civil Engineers, Vol 78, Separate No. 126, 1952 pp. 1-26.

(14) Tannehill, Ivan Ray, Hurricanes, Princeton University Press, Princeton, 1945.

(15) U. S. Weather Bureau, Hurricane Notes, Weather Bureau Training Paper No. 1, 1948.